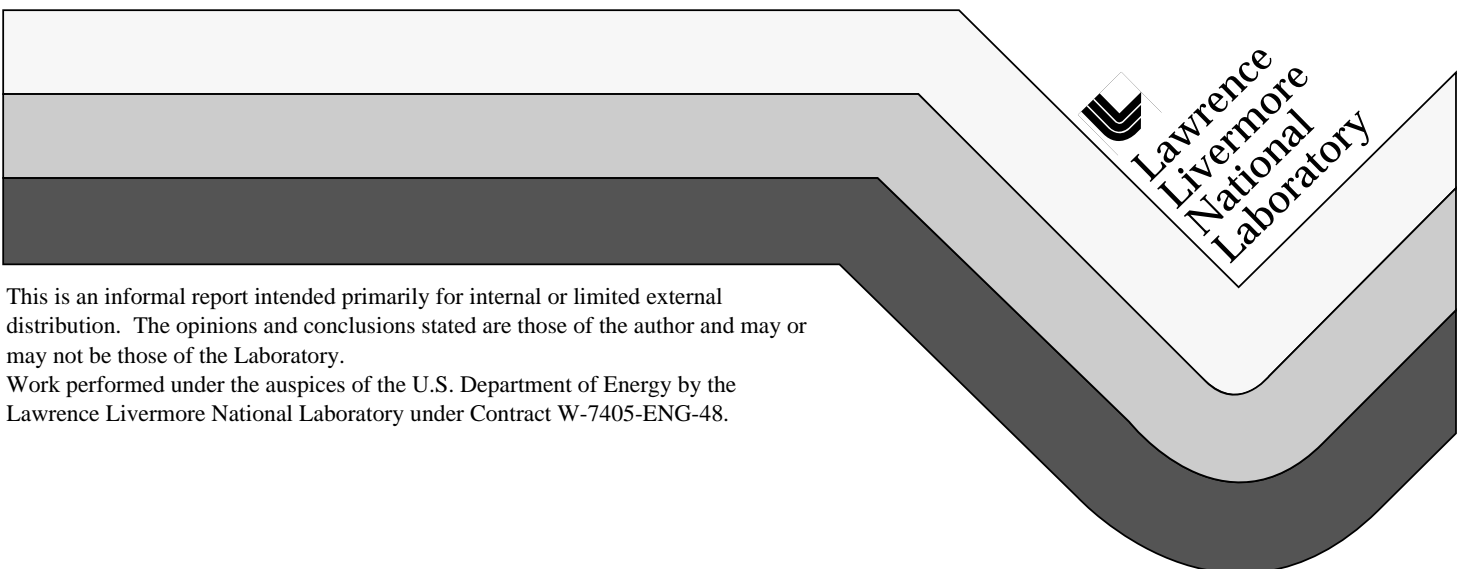


## Pre/Post-Strike Atmospheric Assessment System (PAAS)

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February 3, 1997



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# **Pre/Post-Strike Atmospheric Assessment System (PAAS)**

**S.G. Peglow and J.D. Molitoris**

## **Background**

The Pre/Post-Strike Atmospheric Assessment System was proposed to show the importance of local meteorological conditions in the vicinity of a site suspected of storing or producing toxic agents and demonstrate a technology to measure these conditions, specifically wind fields. The ability to predict the collateral effects resulting from an attack on a facility containing hazardous materials is crucial to conducting effective military operations. Our study approach utilized a combination of field measurements with dispersion modeling to better understand which variables in terrain and weather were most important to collateral damage predictions.

To develop the PAAS wind-sensing technology, we utilized a combination of emergent and available technology from micro-Doppler and highly coherent laser systems. The method used for wind sensing is to probe the atmosphere with a highly coherent laser beam. As the beam probes, light is back-scattered from particles entrained in the air to the lidar transceiver and detected by the instrument. Any motion of the aerosols with a component along the beam axis leads to a Doppler shift of the received light. Scanning in a conical fashion about the zenith results in a more accurate and two-dimensional measurement of the wind velocity.

The major milestones in the benchtop system development were to verify the design by demonstrating the technique in the laboratory, then scale the design down to a size consistent with a demonstrator unit which could be built to take data in the field. The micro-Doppler heterodyne system we developed determines absolute motion by optically mixing a reference beam with the return signal and has shown motion sensitivity to better than 1 cm/s.

The following pages describe the rationale, technical approach and laboratory testing undertaken to demonstrate the feasibility and utility of a system to provide local

meteorological data and predict atmospheric particulate motion. The work described herein was funded by the Laboratory Science and Technology Office as a part of the 1996 Laboratory Directed Research and Development Program at Lawrence Livermore National Laboratory.

## **1.0. PAAS: Motivation for a Compact Lidar**

### **1.1. Overview**

The mission of a Pre-/Post-Strike Assessment System (PAAS) is defined above as being able to assess the local meteorology well enough to accurately determine the three-dimensional extent, along with ground deposition, of a dispersive plume from a target. The system would be emplaced prior to a strike to determine the time frame in which an attack would result in the least collateral damage and continue to operate after the strike to assess actual collateral damage. As such a release could contain a high concentration of hazardous material, the dispersion path is of paramount importance. Many variables affect the plume motion, including temperature, humidity, local terrain and weather. However, the meteorological variable with the most direct effect on dispersion is clearly the wind field. To determine the most accurate estimate of the dispersive flow from any source, one needs the most accurate three-dimensional wind field possible. With an accurate three-dimensional wind field, the influence of local sources can be ascertained [Olivier 1991]. Due to the complexity of the wind field, the most accurate determination should be based on timely range resolved profiling from the surface layer up to the free atmosphere.

In practice, real-time wind profiling of a region from multiple locations is almost never done and one has to rely on a single such profile related to accompanying anemometer measurements. Typically the wind field is

interpolated in a consistent fashion from whatever data is available. This relationship between measurement locations is performed by a wind model. Wind codes also take into account terrain and other meteorological variables to determine a consistent three-dimensional wind field [Foster 1990, Sherman 1978], but the most accurate wind fields are clearly generated from timely range-resolved velocity measurements in the region of interest. Given the wind-field, transport modeling can be performed to determine dispersion [Lange 1978, Leone 1989]. Furthermore, the wind-field and concentration data can be used as input for prognostic modeling [Hodur 1987, Lee 1995] to predict flow and ascertain how regional measurements couple to a larger global picture.

### 1.2. Evaluation of Data on Explosive Detonations

To define the necessary measurements for PAAS we studied and re-analyzed data from various explosive release field experiments. The primary work on cloud rise from explosive detonations was performed by Church (1969). Church performed an in-depth analysis of cloud rise for explosive yield from  $10^2$  to over  $10^7$  pounds of TNT equivalent. Based on Church's analysis, we determined that for amounts of

high explosive equivalent to most conventional, air-dropped weapons, the two-minute cloud rise varies from 200 to 600 meters, with a mean of 400 meters. Explosive energy absorbed by the ground (due to penetration) and the target structure would tend to reduce the mean rise; furthermore flow patterns within the first 200 to 300 meters tend to strongly influence the transport due to localization and net density of the cloud. These conclusions were bolstered by additional research and modeling performed by Shinn (1989) and Baskett (1993). Finally, we examined some of the data from the ROLLER COASTER experiments performed at the Tonopah Test Range in Nevada in 1963, in particular the CLEAN SLATE and DOUBLE TRACKS measurements. Using operational models which are a standard part of the LLNL Atmospheric Release Advisory Capability (ARAC), we had the deposition patterns calculated for stable and unstable atmospheres. A range-resolved measurement of the wind from a balloon-borne radiosonde was utilized to help understand the implications of wind profiling to various altitudes. To do this, we curtailed the sonde measurement at various altitudes and determined the wind field, hence simulating different measurements. These results are shown in Figure 1.

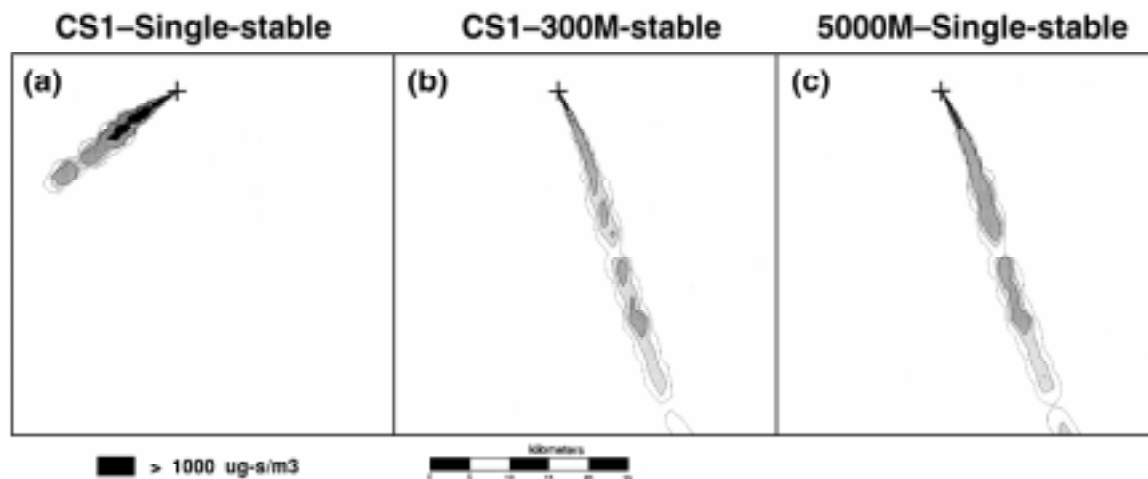


Figure 1) Calculation of deposition pattern for one of the CLEAN SLATE measurements using three sets of wind profile data in a stable atmosphere. (a) single-point anemometry; (b) range-resolved profile to 300 meters; (c) range-resolved profile to 5000 meters (5 km). Note the similarity of b and c. See text for further explanation.

The results indicated in Figure 1a show that single-point anemometry 20 m from ground level was not useful in determining the actual

flow field, probably due to terrain and boundary layer turbulence. A singular range-resolved measurement (profile) in the vicinity of the

release from near ground level to 300 meters, Figure 1b, defined a flow field similar to the full set of measurements taken up to 5 kilometers, shown in Figure 1c. Calculations also verified this result for unstable atmospheric cases, although the difference was not as marked as for the stable atmosphere.

The result that wind profile measurements to altitudes greater than 300 m did not significantly increase the accuracy of the wind field calculation, for the type of conventional weapon explosive releases of interest here is significant. This has direct implications for the size, complexity, cost, and almost every major aspect of an emplaced field sensor. We note that higher altitude wind profile data would make a difference for more powerful explosive events, such as nuclear explosions, but we are primarily interested in conventional weapon strikes and regional (up to 100 km square) areas.

The one additional factor which would significantly improve the wind field determination was a multiplicity of velocity profiles in the area. In most cases, three units emplaced at critical locations were sufficient to accurately determine the plume. In fact, this is much more data than is available in assessing a typical hazardous release. Critical measurement locations are related to the complexity of the terrain near the target. These conclusions were based on researching the literature and experience gained in our previous work; rigorous modeling on ideal unit emplacement was not performed for specific scenarios.

### 1.3. Selection of technique

The conclusions noted above helped focus the original design objective of this project as demonstrating that a velocity-sensing instrument could be built of appropriate size, weight, robustness, and cost for multiple field deployment. If the profiling ability was not cost effective for multiple units, then a central profiler should be deployed in the most critical location and two-point anemometers deployed

in less critical regions. Other factors considered were obtrusiveness and ease of operation. It was not an easy decision to embark on the development of a new remote sensor, as the original project proposal was limited to evaluating and comparing existing techniques concentrating on SODAR (sound detection and ranging) and LIDAR (light detection and ranging).

In fact a wide range of sensors was considered: sonic anemometers, mechanical anemometers, balloon-borne radio-sondes, SODAR, and LIDAR among others. Obtrusiveness or tower emplacement negates some of these. Power or on-station time requirements for continual use negated others. Finally, the necessity for continual range-resolved data limited the options to SODAR and LIDAR. SODARs have the advantage that they are commercially available, but their high-decibel sound emissions make them very obtrusive and even mini-SODARs are as large as a small car. LIDAR conformed to the project needs in every way except cost and robustness.

Wind-sensing LIDARs are commercially available, but they cost in excess of \$600K for a basic unit and over \$1M for a complete system. Existing systems also tend to be fragile. Our original project proposal was to borrow or lease one of these units to perform experiments and explore how it could be modified. Two factors changed this: (1) the determination that an operational ceiling of 300 meters was sufficient for a tactical unit and (2) the commercial availability of relatively inexpensive, high-coherence lasers which were extremely compact, robust and energy efficient [Davis 1996, Kane 1995]. These solid-state diode pumped units could even be dropped from over five feet onto a hard surface and still function.

## 2.0. Theory, Design, Development of a LIDAR Unit

### 2.1. Laser Doppler Velocimetry

Laser Doppler Velocimetry (LDV) is by no means a new technique [Durst 1976, Bilbro 1980]. The way the principle works is to actively probe with a highly coherent source of light. The coherence length of the laser is one factor which determines the maximum range which can be probed. As the coherence length ( $L_c$ ) and

coherence time ( $t_c$ ) are inversely related to the laser line width ( $\Delta V_L$ ) by the relations [Davis 1996]:

$$L_c \sim C / \Delta V_L; t_c \sim 1 / \Delta V_L$$

where  $C$  is the speed of light. It follows that a narrow line width laser is required for a high coherence and for LDV. For PAAS, a coherence length greater than twice the maximum range (or  $> 600$  meters) is required. The coherence time is one measure of the maximum possible data sampling period. All three lasers used in our development had line widths of less than 5 kHz over periods of 1 msec. Laser specifications list the coherence length as  $> 1000$  meters, when in fact the coherence length corresponding to this line width is  $> 60$  km with coherence times of about 0.2 ms.

The coherence of the laser guarantees a negligible wave train shift in the absence of motion. Any shift in the return signal within half the coherence length is due to the Doppler shift from motion of the scatterer. For our case the Doppler formula reduces to

$$\Delta V_D = 2V_{\text{source}} V_o / c$$

where  $\Delta V_D$  is the Doppler shifted frequency,  $V_{\text{source}}$  is the velocity of the scatterer,  $V_o$  is the frequency of the outgoing laser beam, and  $c$  is the speed of light.

The primary mechanism for velocity profiling in the atmosphere is Mie scattering [Measures 1992] from particulates, aerosols, and dust. In this type of interaction laser radiation is elastically scattered from particulates or aerosols of a size comparable to the wavelength with no change in frequency from the scattering mechanism. In Mie scattering, any change in the observed return frequency can be attributed to a Doppler shift from motion of the scatterer.

The PAAS mission is well within the boundary/surface layer of the atmosphere. This region of the troposphere has an abundance of particulate matter which makes it ideal for LDV. Jursa (1985) has tabulated vertical aerosol distributions (see Fig. 2) from the surface layer into the upper reaches of the stratosphere (to altitudes of greater than 70 km). The inset to Figure 2 shows an enlargement of the aerosol

profile within the boundary layer region. The distributions are for three different models with different surface visibility. Although the attenuation coefficient here is for the visible, it is similar for the near-infrared (0.7 to 1.0 microns) [Wolfe 1989]. The increased attenuation within the boundary layer corresponds to an enhanced aerosol number density, but not all these are suitable scatterers for LDV. For Mie scattering, the size of the scatterer must be comparable to or greater than the wavelength of the laser radiation, so the aerosol size distribution becomes important. Figure 3 shows aerosol size distributions for variations of two different atmospheres. Keeping in mind that nearly all LDV lidars normally operate at 10 microns, these distributions show an increase of four to five orders of magnitude in the number of available aerosols at 1 micron than at 10 microns. Furthermore, by limiting the operation of a tactical wind profiling lidar to the lower 300 meters of the atmosphere, one takes advantage of abundance of dust and other large airborne particulates within this region [Stull 1988] in addition to the ambient aerosols.

Typical LDV lidars have been based on large carbon-dioxide laser systems [Billbro 1980, Durst 1976] as they have sufficient coherence properties to ensure measurements to altitudes of several kilometers. During the course of our research we have determined that a tactical wind profiling lidar does not have to probe at these altitudes; it therefore follows that the required laser power can be scaled down due to the increased aerosol number density in the tactical region of interest as long as the coherence length of the laser is sufficient for LDV. Use of a shorter wavelength laser increases the strength of the return signal and justifies a further reduction in laser power. Using available data and making our initial calculations we determined that a LDV lidar with a wavelength of one micron required as little as 10 mW of average laser power for point anemometry (15 meters from aperture) and as little as 50 mW of average power for a range-resolved measurement to 300 meters. The laser power estimate for point anemometry is confirmed in the literature [DiMarzio 1991] and discussions with those in the lidar community [Goldsmith 1996; Arens 1995] verify our calculations.

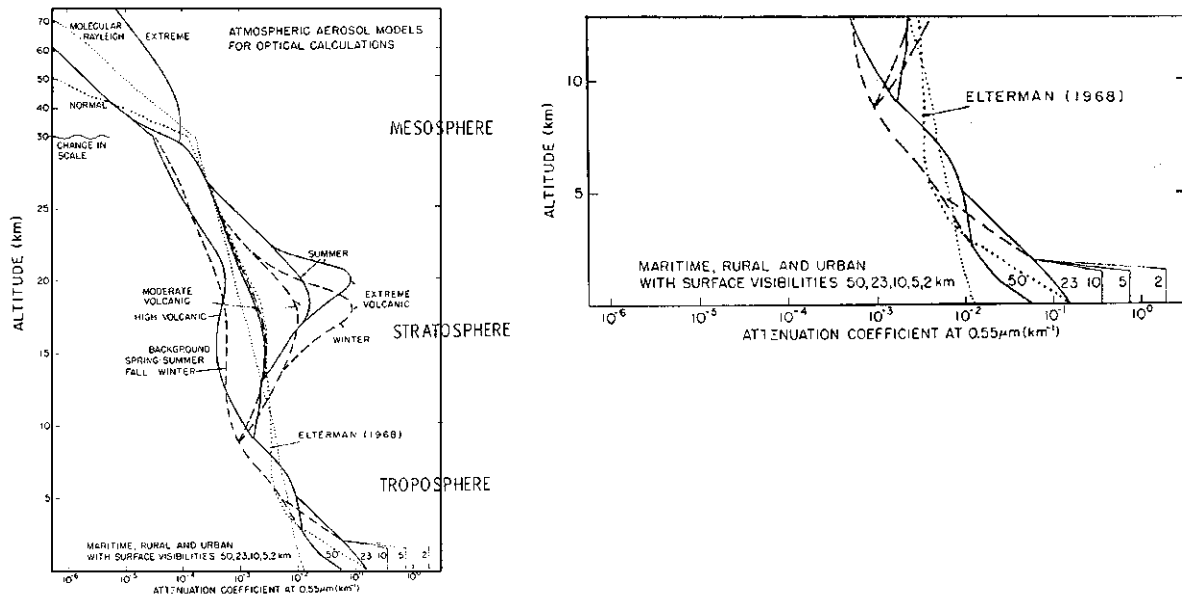


Figure 2) Atmospheric aerosol profiles from various sources [Jursa 1985]. The inset shows the increased attenuation due to a higher number density within the boundary layer.

## 2.2. LIDAR Design

**Heterodyning.** Critical to LDV is the ability to determine the Doppler shift. Furthermore, due to the coherence criteria discussed above the sampling time must be short (less than 1 ms), but multiple samples can be summed to increase signal fidelity if necessary. The best way to determine the Doppler shift in short sampling times is by optical heterodyning. Clear discussions of this can be found in many laser and electro-optic textbooks (for example, see Davis [1996]), so only issues concerning our instrument and data will be mentioned here. Figure 4 illustrates the arrangement for optical heterodyning. The key point is that two beams, a return signal and a local oscillator signal are mixed coherently on the detector. As the detector responds to the incident light, the current is proportional to the sum squared of the two electric fields. As the detector cannot respond to rapidly oscillating frequencies, it only responds to the amplitudes and the

difference frequency of the two signals (assuming that the difference frequency is within the response range of the detector). As long as the two frequencies are sufficiently different the direction of a frequency shift can be ascertained. So, the Doppler shift can be used to determine not just the magnitude of the velocity, but whether it is toward or away from the observer.

To guarantee that the two frequencies are sufficiently different, one either uses two lasers, or directs a small fraction of the laser beam into a modulator and then mixes it with the return signal. This is called the local oscillator signal. A final advantage of heterodyning worth mentioning here is that the technique is particularly useful for amplifying a weak signal. This is because the electric field of a weak incoming signal is multiplied by the local oscillator field in the mixing process, thus boosting it.



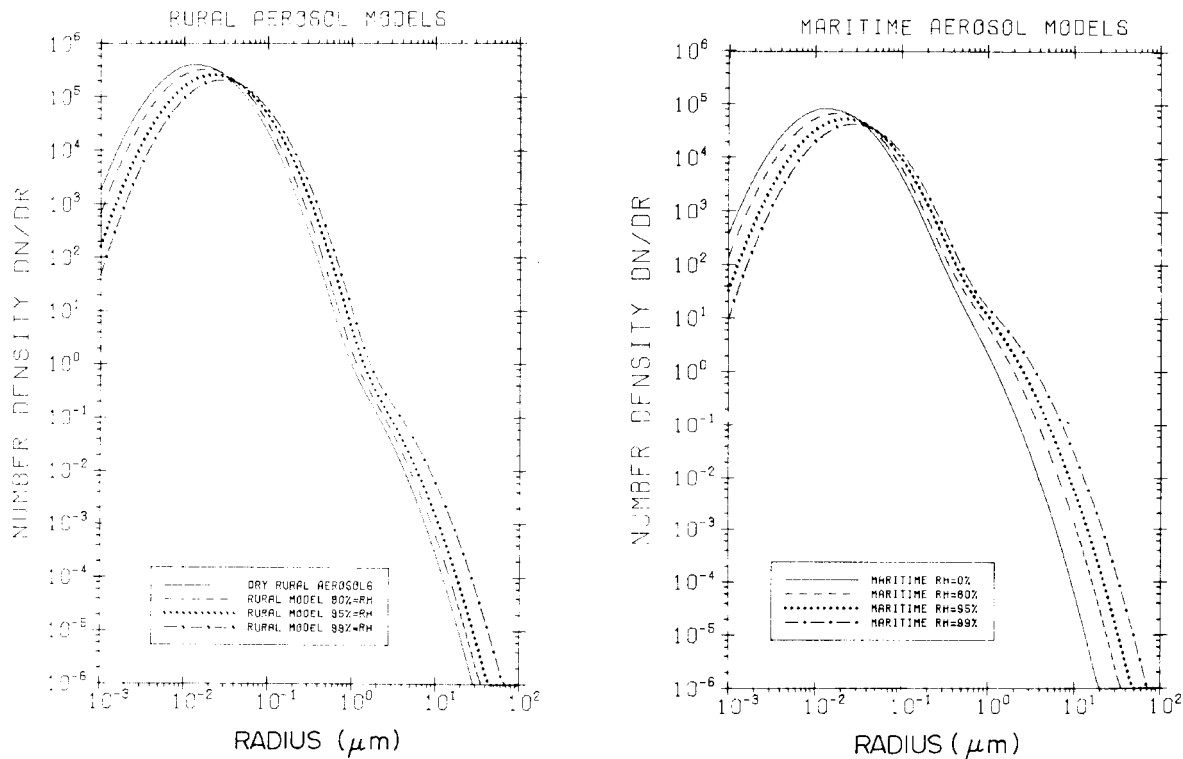


Figure 3) Atmospheric aerosol size distributions for various conditions in two different types of atmospheres [Jursa 1985].

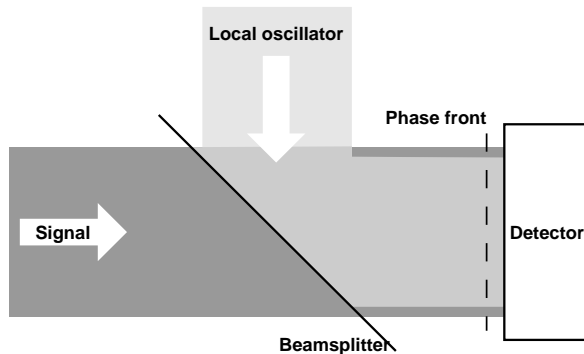


Figure 4) Schematic arrangement for optical heterodyning.

**CW technique (Ranging methods).** The above defines the detection method of our LIDAR and its ability to determine the Doppler shift, but a LIDAR must also determine range. Ranging is performed in most LIDARs by pulse compression and timing [Measures 1992]; a pulse is transmitted and the backscattered return signal is detected as a function of time to a point

where its intensity is within the noise. For our tactical application this technique is disadvantageous. The main disadvantage is that the minimum range gate can typically be several hundred meters from aperture; thus the system would be blind to the region of interest. Furthermore, it is the pulsing and timing which complicate the LIDAR, making it more fragile and unwieldy. For these reasons we picked a technique which was simple and inherently robust.

We run the laser in a continuous wave mode (no pulsing) and focus the beam to maximize the return signal from a region of interest. By insuring the system is diffraction limited, no off-axis rays make it to the detector, only those from the focal region. A discussion of CW lidar using the focus technique for ranging can be found in Lenschow [1986]. Using Gaussian beam propagation we calculate the range resolution in terms of depth-of-field as a function of signal return for various size optics. Figure 5 shows how the signal range fidelity improves as the

size of the optic is increased. We set minimum acceptable design goals at 50% signal return and 20 meter range resolution at 80% return. For these criteria the calculation shows that the optic size must be 8" or greater. However, for a 4" diameter optic, a 50% signal return has a range resolution of better than 10 meters at a distance from aperture of 300 meters, which may be acceptable for a tactical unit. For this reason, most of the laboratory evaluations described below were performed with a 4" optic. One distinct operational advantage of this LIDAR is that the beam is expanded to the diameter of the telescope, thus making it aperture eye-safe. In fact, there is only a short window starting from near focus at which the unit is not eyesafe.

**System Design.** The system elements discussed above can be assembled into a very neat fiber optic coupled design as shown in Figure 6. This design evolved from various system demonstrations during the project. The

offset locking device frequency locks the two lasers. The same optic (telescope) is used for transmitting and receiving. Local oscillator and return signals are mixed in the fiber optic couplers connected to the detector, which here is shown as a balanced receiver. The advantage of a balanced receiver is twofold. First, it picks up both mixing channels which are equivalent. Secondly, it cancels out heterodyne intensity noise which results in a further sensitivity gain by dropping the noise floor.

### 2.3. LIDAR demonstration unit and evaluation

During the course of this research three design iterations were evaluated in the laboratory. The first system was a homodyne unit which did not frequency shift the local oscillator in relation to the probe beam. This system utilized the most powerful lasers, but was not as compact and did not follow the

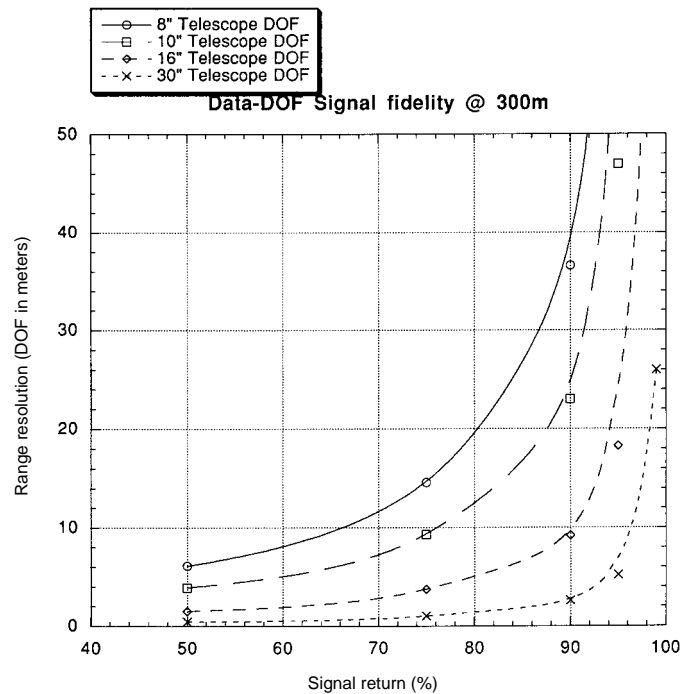


Figure 5) Comparison of range resolution for various diameter optics in CW LIDAR. Larger diameter telescopes can be used to make precision measurements within the boundary layer; smaller diameters are appropriate for tactical units. The smallest acceptable diameter is 4". The depth of field (DOF) is the range resolution, which is plotted here as a function of the percentage of signal return.

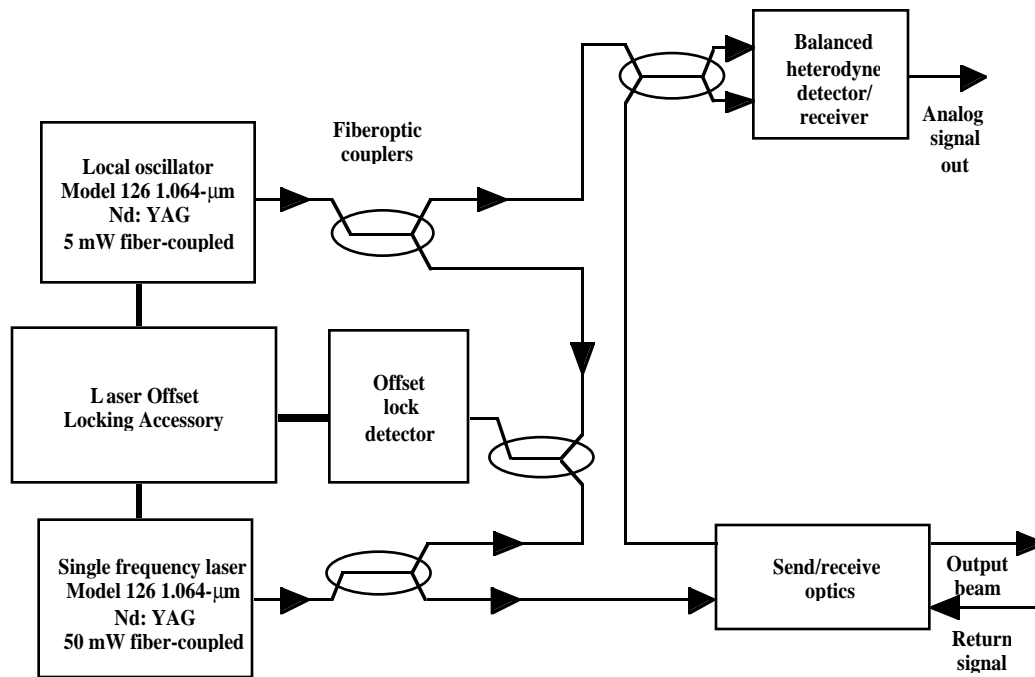


Figure 6) Block diagram of final photonics design. The fiber optic coupling makes the final system more robust and trouble free.

concept design described above. As a homodyne system, it was able to determine the Doppler shift magnitude, but not direction. Due to the laser power it was able to detect aerosol motion, but that data is not representative of a compact tactical unit.

The first system representative of the design concept is shown in Figure 7. most other systems count photons directly and do not perform heterodyne mixing. Even with standard size optical components the system fits in a 14" x 29" footprint, which attests to the inherent compactness. With available miniature components this footprint can be reduced by 40% and with fiber optic coupling it can be engineered into a number of configurations.

The 9.5 inch height of the enclosure was meant to allow space for environmental system control necessary for field measurements. Unlike the concept design above, this system is open beam/free space and not optically coupled, hence it is much more susceptible to environmental conditions. Our budget did not allow us to construct a fiber optic coupled system. Although more sensitive to conditions,

the free space system did have the advantage of allowing us to configure it in a number of different ways to explore optimization and evaluate different concepts to increase sensitivity.

To illustrate the difference in homodyne and heterodyne mixing, a typical return signal is shown in Figure 8. This data is a velocity-shifted return signal displayed in frequency space. Here, the peak at zero frequency is an artificial reference generated by the spectrum analyzer. The peaks to either side of the zero reference are the homodyne peaks from either of which the Doppler shift can be determined. Any motion toward or away from the system creates two homodyne peaks, equally spaced from zero; hence the direction cannot be ascertained. These data also show the local oscillator signal at 60 mHz and the offset velocity peak to the right of it. This is the heterodyne peak. Note that there is only one peak and that the signal intensity is an order of magnitude greater than the homodyne peaks, thus illustrating the amplification of the local oscillator mentioned above.

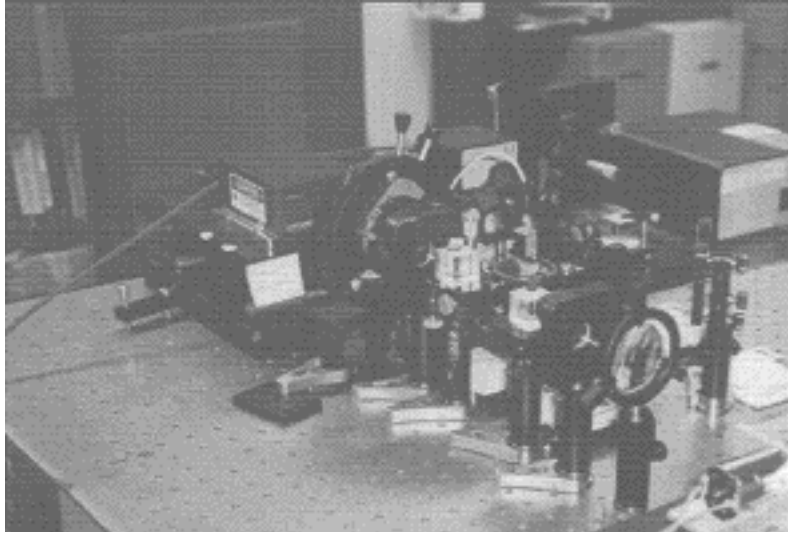


Figure 7) Benchtop heterodyne lidar evaluation system. This system provided full heterodyne mixing capabilities and measured velocity in near real time.

Figure 9 illustrates the velocity discrimination of this design. With this fidelity signal, measurements from 0.25 m/sec to over 50 m/sec are possible. In the laboratory it was not possible to generate velocities of over 18 m/sec for either particles or as a reference. The data in the figure demonstrate the system's ability to resolve range. In this data there is a rotating wheel in the optical path. Focusing at

$\pm 75$  cm from the object, even a moving hardbody barely registers a signal out of the noise. These raw data are averaged over periods of time longer than coherence time; for an acquisition system sampling within the coherence time the signal range resolution should approach the design expectations. The data in Figure 10 was taken with a 4" optic at near focus (15 meters from aperture).

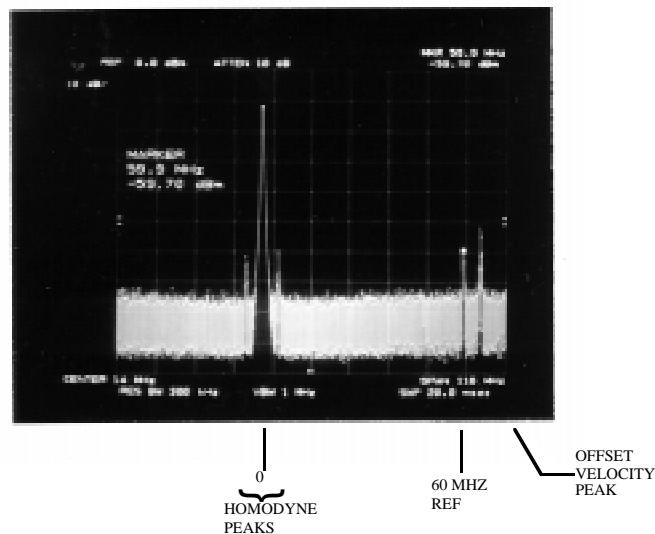


Figure 8) Spectrum analyzer display of a typical return signal in frequency space. The peak at zero frequency is an artificial reference generated by the spectrum analyzer. The peaks to either side of the zero reference are the homodyne peaks from which velocity is calculated.

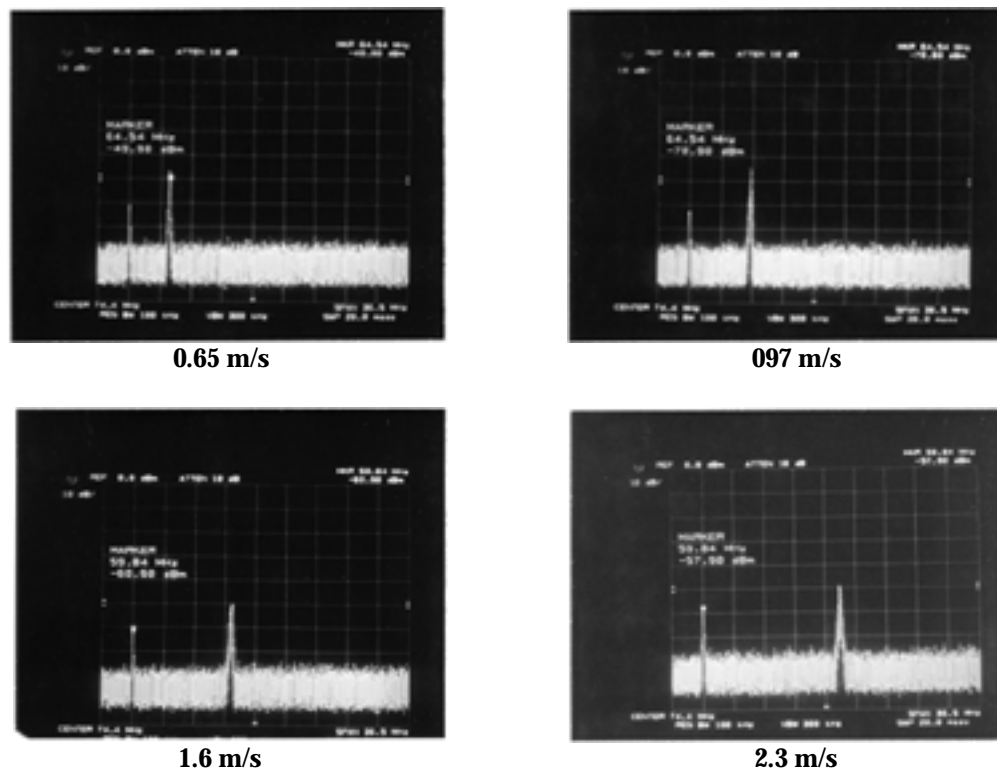


Figure 9) Velocity discrimination data of the heterodyne LIDAR.

Figure 11 demonstrates the ability of the heterodyne lidar to determine direction. These data were taken with an ambient air jet tuned toward and away from the beam via a nozzle/funnel system. The width of the signal is due to the velocity jitter within the airjet (this is not the smooth flow from a wind tunnel). The degraded intensity of the signal may be attributed to the averaging effect of the spectrum analyzer. The laser used in this measurement was of higher power than that used for a typical system evaluation.

## Summary

The PAAS project was proposed to show the importance of local meteorological conditions in the vicinity of a proliferant site and demonstrate a technology to measure these conditions, specifically wind fields. Our approach utilized a combination of field measurements with dispersion modeling to better understand which

variables in terrain and weather were most important to collateral damage predictions.

During October and November 1995, we used a large phased array SODAR (Sound Detection And Ranging) to look at wind fields on site at LLNL. A parallel modeling and analysis effort showed that the field data having the highest impact on atmospheric dispersion from typical sites and strikes was in fact range-resolved wind data from surface level to about 300 meters taken with at least 20 meter resolution. As the SODAR was obtrusive and not easily transportable, we examined a full range of other methods for wind field analysis. We decided to focus the project on the development of a compact, portable LIDAR (Light Detection And Ranging) and to perform range-resolved wind measurements from near ground level to at least 300 meters at spatial resolutions comparable to the SODAR for purposes of calibration.

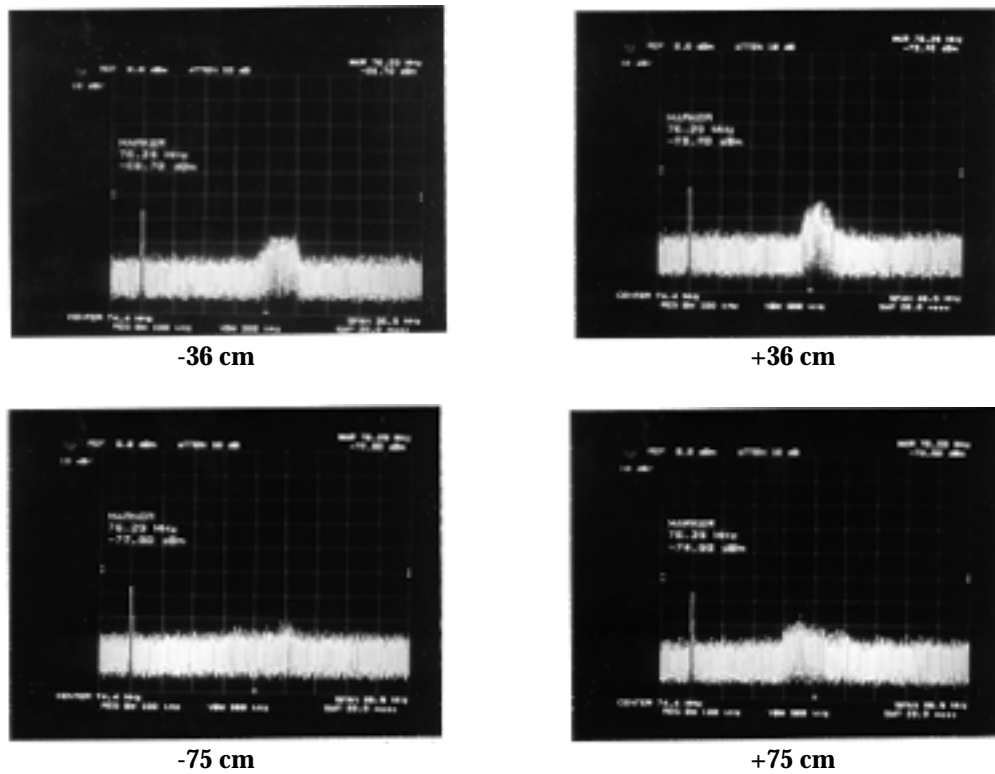


Figure 10) A demonstration of range resolution in the extreme case of a moving hardbody in the optical path.

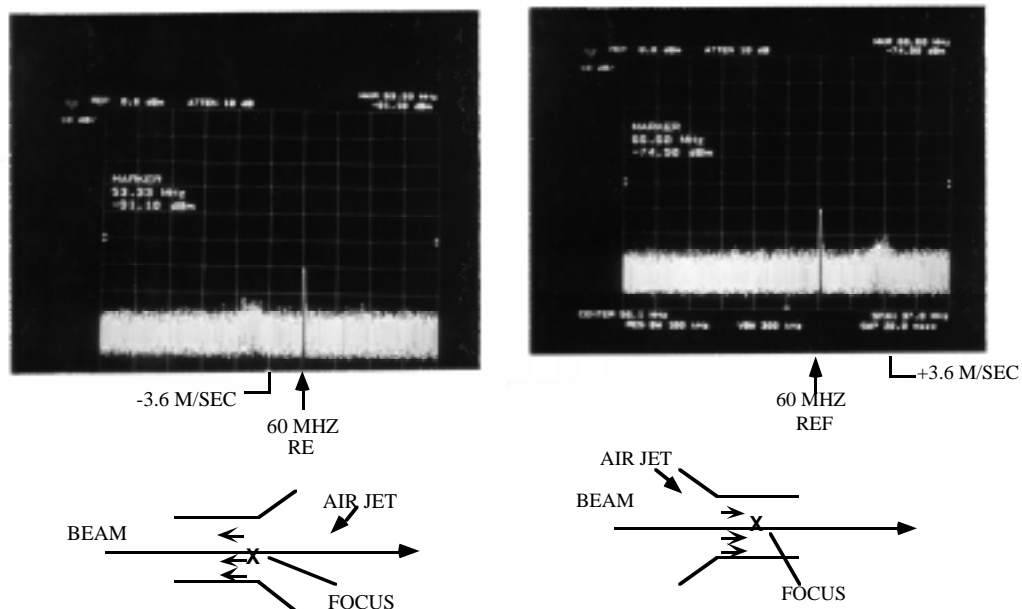


Figure 11) Ambient aerosol peak demonstrating ability of the LIDAR to determine particle direction.

To develop the PAAS wind-sensing LIDAR, we utilized a combination of emergent and

available technology from micro-Doppler and highly coherent laser systems. The method used

for wind sensing for this LIDAR is to probe the atmosphere with a highly coherent laser beam. Any motion of the aerosols with a component along the beam axis leads to a Doppler shift of the received light. Scanning in a conical fashion about the zenith results in a more accurate measurement of the wind velocity.

The major milestones accomplished were to verify the design by demonstrating the technique in the laboratory, then scale the design down to a size consistent with a demonstrator unit which could be built to take data in the field. Because of the abundance of 1 micron laser optics and instrumentation available, we were able to demonstrate the technique and experiment with variations of the primary design. We developed new ways to tune the system and correctly align the heterodyne

optical mixing channel which measures the Doppler shift. Furthermore, we were able to rebuild commercially available telescopes to optimize their performance and optimize signal/noise for lower-power sources.

The micro-Doppler heterodyne system we developed determines absolute motion by optically mixing a reference beam with the return signal and has shown motion sensitivity to better than 1 cm per second. The entire heterodyne field unit, excluding the portable data analysis unit, has a footprint of less than 14 x 24" and is less than 8" high as shown in Figure 12, which was well within acceptable size constraints for a PAAS field unit.

As a result of this research, we have demonstrated the feasibility of using a small, lightweight laser-based system to provide in-situ meteorological information. This information has been shown to be critical in making accurate predictions of hazardous material dispersion resulting from military operations.



Figure 12) Model of portable PAAS unit.

## Acknowledgements

The authors acknowledge the support of LLNL LDRD through the NAI Directorate without which this research would not have been possible. We would also like to acknowledge the sincere interest of Dr. Greg Simonson and Dr. Walt Soy who encouraged us to use the offset homodyne design instead of a two-laser heterodyne system. Many valuable discussions with Dr. Peter Young help continually refine the design of the lidar. Finally, the help of Ms. Rosalie Powers was much appreciated during the course of this project.

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